Renewable and Sustainable Energy Reviews 18 (2013) 174–183

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biomass gasification for electricity generation: Review of current technology barriers

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ARTICLE INFO

Article history:
Received 3 April 2012
Received in revised form
10 October 2012
Accepted 11 October 2012
Available online 9 November 2012

Keywords:
Gasification
Biomass
Syngas
Catalysts
Tars
Ashes
Technology barriers

ABSTRACT

Biomass gasification has yet to consolidate its position compared to other techniques for exploiting biomass energy.

Neither the research conducted nor the plants built in recent decades, nor even government support for this technology, have provided a sufficient boost to increase the level of implementation of gasification despite its advantages in aspects such as greater efficiency and the reduction in CO_2 emissions, as there are numerous other methods of biomass energy conversion that provide stiff competition.

In this paper, gasification techniques have been reviewed in depth and the main factors to be considered in the design of a gasification plant have been outlined.

It is observed that there are a great number of factors involved in design and operation of a gasification plant, and many of them are critical. Moreover, having designed a plant according to certain specifications, there is a high probability that these initial conditions can vary, causing a malfunction of the plant.

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.10.021

1. Introduction

Gasification is a thermochemical partial oxidation process in which carbonaceous substances (biomass, coal, and plastics) are converted into gas in the presence of a gasifying agent (air, steam, oxygen, CO_2 or a mixture of these). The gas generated, commonly referred to as syngas (synthesis gas), consists mainly of H_2, CO, CO_2, N_2, small particles of char (solid carbonaceous residue), ashes, tars and oils.

The versatility of gasification is that it can be used for producing syngas, H_2 or other liquid fuels, and can thereby meet the demand for electricity or thermal energy. Furthermore, the resulting fuel can be transported with high energy densities, enabling the generation of electricity to be centralized based on disperse gasification systems.

Biomass gasification has yet to become consolidated as a mature technology, and in most markets it cannot compete with other methods of energy conversion [1]. According to Dasappa, the performance of a 100 kW gasification plant with a downdraft reactor (a type of reactor in which biomass and the gasifying agent come into contact via parallel flows) connected to the grid is unsatisfactory, operating over 1000 h and supplying energy to the grid for only 70 h [2]. So where are the barriers to the definitive development of this technology? Are these limits insurmountable over the short to medium term, or are there still design options that will enable gasification to become a truly attractive way of generating electricity?

The key issues to be faced when designing a gasification plant are the gasifier, its operation and the treatment and adaptation of the syngas generated, without forgetting the paramount importance of biomass preparation and logistics. These two latter aspects are not the primary focus of this paper, but this should not be taken to mean they are any less important.

Gasification may appear to be a rigid technology, as it requires a thorough adaptation of the fuel to be processed and, once this has been achieved and the operating parameters have been fine-tuned, it allows little operating flexibility. This means that any variations in the specific characteristics of the biomass will have unwanted consequences for the gasification process, such as operating instability, loss of performance, problems of scaling, etc.

2. Fundamentals of gasification

Gasification takes place at high temperatures (between 500 and 1400 °C) at a range of pressures that runs from atmospheric pressure to 33 bar [3].

According to Prabir Basu [4] the different stages of gasification overlap and there is no clear limit between them. Those stages (Fig. 1). are

- *Heating and drying of solids*: The typical moisture content of freshly cut wood ranges from 30% to 60%, and may exceed 90% in some types of biomass. Every kilo of moisture in biomass requires a further 2260 kJ to vaporize the water, and that energy cannot be recovered. When little can be done to dry the water present inside the cell walls of biomass the utmost effort must be made to eliminate surface moisture. Depending on the moisture level of biomass, drying processes are usually needed, preferably prior to entry in the gasifier. For gasification, moisture content should be between 10% and 15% [4].
- *Pyrolysis*: This process occurs at between 150 and 400 °C and results in the formation of a solid carbonaceous waste known as "char" along with gases (condensable and non-condensable). The main components of this gaseous phase are H_2O, CO_2, H_2, hydrocarbons and smaller quantities of other compounds (organic acids). The hydrocarbon fraction comprises methane and organic compounds known as tars (which are a problem above a certain concentration). The breakdown of this hydrocarbon fraction may be influenced by various parameters such as particle size, temperature, pressure, heating time and residence time. Pyrolysis is a stage where char is eliminated but no hydrogen is added [4].

Pyrolysis in itself is a thermochemical process used to convert biomass into liquid fuel or bio-oil. Pyrolysis can be divided into three subclasses: slow pyrolysis, fast pyrolysis and flash pyrolysis [5]. The main operational parameters are outlined in Table 1.

- *Oxidation or partial combustion* of some gases, steam and char by a gasification agent, usually air. Part of the compound is converted to CO, CO_2 and H_2O. The energy needed for the reduction and pyrolysis reactions is generated at this stage.
- *Reduction or gasification* of the char produced during pyrolysis. The char is converted mainly to CO, CH_4 and H_2. Biomass char is usually more porous and reactive than coke. Its porosity level is between 40% and 50%, while that of char is between 2% and 18%. Moreover, the pores in biomass char are larger than those in char from fossil char. The differences are large enough for the gasification reactions to be different from those of coal, lignite or peat. For instance the reactivity of peat char decreases with conversion and over time, while that of biomass char tends to increase. This opposite tendency may be due to the increase in catalytic activity of the alkaline metals in biomass char.

The gasification of biomass char entails several reactions between the char and the gasifying agents which produce CO and H_2. The main reactions that take place in the gasification process are shown in Table 2.

The first two reactions (R1 and R2) are endothermic and the heat required to produce them is supplied mainly by the oxidation reaction (R5), which is highly exothermic.

The result of this process is a gas made up mainly of CO, H_2, N_2, CO_2, H_2O and hydrocarbons. Very small quantities of NH_3, H_2S and tars are also obtained. After treatment this gas can be burned cleanly to produce mechanical or electrical energy with no waste products, well within environmental regulations on pollutant gas emissions.

3. Biomass

3.1. Biomass composition

It is often affirmed that scant attention is paid to the biomass to be used in a gasification process, and that the focus is on the

Fig. 1. Gasification process steps.

Table 1
Operating parameters of the pyrolysis process [5].

Pyrolysis	Heating rate (K/s)	Residence time (s)	Temperature (°C)	Particle size (mm)	Product
Slow	< 1	300–1800	400 600	5–50	Char Gas, oil, char
Fast	500–10^5	0.5–5	500–650	< 1	70% oil 15% char 15% gas
Flash	> 10^5	< 1 < 1 < 0.5	< 650 > 650 1000	< 0.2	Oil Gas Gas

Table 2
Main gasification reactions at 25 °C.

Char or gasification reactions	
R1 (Boudouard)	$C+CO_2 \leftrightarrow 2CO+172$ kJ/mol
R2 (Steam)	$C+H_2O \leftrightarrow CO+H_2+131$ kJ/mol
R3 (Hydrogasification)	$C+2\,H_2 \leftrightarrow CH_4-74.8$ kJ/mol
R4	$C+0.5O_2 \rightarrow CO-111$ kJ/mol
Oxidation reactions	
R5	$C+O_2 \rightarrow CO_2-394$ kJ/mol
R6	$CO+0.5O_2 \rightarrow CO_2-284$ kJ/mol
R7	$CH_4+2O_2 \leftrightarrow CO_2+2H_2O-803$ kJ/mol
R8	$H_2+0.5O_2 \rightarrow H_2O-242$ kJ/mol
Shift reaction	
R9	$CO+H_2O \leftrightarrow CO_2+H_2-41.2$ kJ/mol
Methanization reactions	
R10	$2CO+2H_2 \rightarrow CH_4+CO_2-247$ kJ/mol
R11	$CO+3H_2 \leftrightarrow CH_4+H_2O-206$ kJ/mol
R14	$CO_2+4H_2 \rightarrow CH_4+2H_2O-165$ kJ/mol
Steam reactions	
R12	$CH_4+H_2O \leftrightarrow CO+3H_2+206$ kJ/mol
R13	$CH_4+0.5O_2 \rightarrow CO+2H_2-36$ kJ/mol

plant's technological design, ignoring the fuel, which leads to numerous operational problems.

Concerning the fuel, biomass is a heterogeneous mixture of organic matter and, to a lesser extent, inorganic matter, including several solid and liquid phases with different contents.

The diversity of biomass fuels (agricultural wastes, energy crops, forestry wastes, industrial wastes, etc.) renders it essential to characterize them thoroughly, as this will have a direct impact on the design of the power plant that will convert them into electricity. This should be done prior to the choice of the technology to be used with a view to avoiding subsequent problems.

There is currently deemed to be a need for a more detailed investigation into the study and characterization of the biomass that can be used for energy purposes, as less is known about these fuels than about fossil fuels such as coal [6]. For example, some biofuels, such as oat hulls, have recorded unsatisfactory results in gasification processes, producing a syngas with a very low calorific value [7], so their use is not recommended in processes of this nature.

Vaezi et al. [8] have developed a numerical algorithm that simulates the gasification of 80 types of biomass. This makes it possible to choose the most suitable type of biomass fuel for obtaining syngas with particular characteristics in a moving/fixed bed atmospheric reactor.

Another case analyzed in the laboratory is that of Qin et al. [9], in which the syngas generated in an atmospheric entrained flow

Table 3
Considerations about the current main types of gasifiers [25,53–56].

GASIFIER	Downdraft	Updraft	Bubbling fluidized bed	Circulating fluidized bed	Entrained flow bed	Twin fluidized bed
Technology	Simple and proven. A simple reactor with relatively low investment cost		Plants with higher investment costs. Proven technology with coal		Complex construction	Complex construction
Fuel specifications	< 51 mm	< 51 mm	< 6 mm	< 6 mm	< 0,15 mm	< 6 mm
Maximum fuel moisture (%)	25	60	< 55%	< 55%	< 15%	11–25
Gas LHV (MJ/Nm³)	4.5–5.0	5–6	3.7–8.4	4.5–13	4–6	5.6–6.3
Tar (g/Nm³)	0.015–3.0	30–150	3.7–61.9	4–20	0.01–4	0.2–2
Ash and particles in syngas	Low	High	High	High	Low	High
Reaction temperature	1090 °C		800–1000 °C		1990 °C	800–1000 °C
Ash melting point	> 1250 °C	> 1000 °C	> 1000 °C		> 1250 °C	> 1000 °C
Syngas output temperature	700 °C	200–400 °C	800–1000 °C		> 1260 °C	800–1000 °C
Admissible powers	Up to 1 MWe	Up to 10 MWe	1–20 MWe	2–100 MWe	5–100 MWe	2–50 MWe
Residence time	Particles are in bed until its discharge		Particles spend substantial time in bed.	Particles pass repeatedly through the circulation loop (few seconds)	Very short (few seconds)	Particles spend substantial time in bed.
Carbon conversion efficiency	High	High	High. Loss of carbon in ash.	High	High	High
Process flexibility	Very limited. Any change in process variables needs a new design		Flexible to loads less than design		Very limited. Size and energy content of the fuel must be in a narrow range.	Flexible to loads less than design
Temperature profile	High gradients		Vertically almost constant. Little radial variation	Vertically almost constant	Temperatures above the ash melting temperature	Constants in each reactor
Hot gas efficiency	85–90%	90–95%	89%	89%	80%	90–95%

reactor at high temperatures (up to 1350 °C) was very similar for cereal straw and wood.

3.2. Preparing the biomass

The preparation of the biomass should be consistent with the gasifier in which it is to be processed. Biomass pre-processing phases have a major impact on gasification outcomes.

Biomass size is a factor that needs to be considered in gasification processes. In an external circulating countercurrent moving bed (ECCMB) gasification system with pine sawdust, Zou et al. [10] show at experimental level that a biomass particle size in the range of 0–1.19 mm has no significant influence on product gas composition.

Perez et al. [11] conducted an experiment with a downdraft reactor and found that biomass (pine bark) behaves differently according to its size. They observed that an increase in particle size led to lower biomass consumption rates, fuel/air equivalent ratios, maximum process temperatures, and consequently lower flame front velocities. They found 2–6 mm to be the optimum biomass particle size.

An experiment with a 10 kWt updraft reactor conducted by Saravanakumar et al. [12], revealed that when the reactor was fed with long stick wood of length 68 cm and thickness 6 cm the efficiency level obtained was 73%, which means that gasifiers with biomass requiring little preparation could be used for development in rural areas.

Xiao et al. [13] observe that pyrolyzing biomass at temperatures of around 400 °C is a promising option for entrained bed gasifiers. Pyrolysis removes the most oxygenated components from the biomass, thereby increasing its energy density. Torrefaction (pyrolysis at a temperature of around 200–300 °C in an inert atmosphere) is also considered a pre-processing option prior to gasification, as it considerably increases energy density and reduces intrinsic reactivity (the fuel's capacity for auto-experiencing unexpected reactions that degrade it). This technique is currently the subject of intense research [14].

The fluidized bed gasification of untreated and pre-treated olive residue and pre-treated olive residue mixed with reed, pine pellets and Douglas fir wood chips was studied by Link et al. [15]. Leaching was used as a pre-treatment process targeted on the elimination of alkali metals such as K and Na as well as chlorine to reduce/eliminate the ash-related problems during gasification. The lower total tar yield of the producer gas in the case of leached olive residue was observed compared to untreated olive residue. This is an important effect on the syngas quality. The leached olive residue was better than any other fuel/mixture tested [15].

The gasification of pelletised biomass in downdraft reactors has also been analyzed by some authors [16]: when this biomass is used as the sole fuel the productivity and stability of the gasifier decrease due to increased head losses. However the syngas produced has a good composition (H_2 17.2%, N_2 46.0%, CH_4 2.5%, CO 21.2%, CO_2 12.6% and C_2H_4 0.4%), the amount of syngas produced per kilo of biomass is high (2.2–2.4 N m^3/kg) and its cold efficiency is also high (67.7–70.0%) [16]. The use of this biomass is proposed as a supplement to other fuels to improve the energy content per unit of volume of syngas and reduce average moisture effects.

This prior pre-processing of the biomass produces more uniform fuels, which may solve the problem of the variability recorded by some untreated biomass, which is a source of instability in gasifiers.

Experiments have been conducted by Šulc et al. [17] with a pilot scale gasification unit with a novel co-current, updraft arrangement in the first stage and counter-current downdraft in the second stage, and the two stage process has been found to be more robust from the point of view of changing composition and properties of the feedstock (waste biomass). This would allow greater variability in biomass fuel.

3.3. Fuel moisture content

Moisture content is crucial in the gasification process, as any increase in the fuel's moisture content means that more energy is required for water evaporation and steam gasification reactions, which in turn lowers the gasifier's operating temperature. Bed temperatures remain more or less stable with moisture contents below 15% [18]. Even so, the moisture level of the biomass depends on the gasifier in which it is to be processed: in updraft type reactors it may be as high as 50% [19].

Perez et al. [11] experimented with a downdraft reactor and pine bark as the feedstock, and concluded that the optimum fuel moisture level was 10.62%.

Hosseini et al. [20] conducted a thermodynamic analysis of the effects of moisture on the exergy efficiency of gasification with air and steam with sawdust. When the moisture fraction of the feed biomass entering the gasifier was increased from 0.15 to 0.25 (kg of moisture to kg of wet biomass) the exergy efficiency of the steam–biomass gasification processes decreased from 17.8% to 16.4%. This change was from 19.1% to 18.4% for the air–biomass gasification process.

Fluctuations in biomass moisture content lead to variations in bed temperature, and this produces changes in the composition of the syngas generated, with this being one of the causes of instability.

Experiments have been conducted by Šulc et al. [17] with variations in fuel moisture levels in a pilot scale gasification unit with a novel co-current, updraft arrangement in the first stage and counter-current downdraft in the second stage. Fluctuating moisture and nitrogen contents in feedstock had less impact on the composition of the resulting fuel gas in the two-stage process.

Syngas composition is linked to biomass moisture content. Thus, the molar fraction of CO increases for dry fuels, while for moister fuels the molar fraction of CO_2 increases, reducing the calorific power of the syngas and, therefore, process efficiency, according to tests conducted in an updraft fixed bed gasifier with air [7].

4. Selection of the gasifier

A gasifier is the main component of a gasification plant. It is responsible for keeping syngas production as steady as possible. Fed by the biomass considered at the planning stage, it should fluctuate as little as possible in response to variations in the biomass. The gasifier is where the biomass fuel and the gasifying agent are mixed to a lesser or greater extent, in some cases together with other inert materials, catalysts or additives, and where the reactions in the gasification process take place:

The way in which the reagents, biomass and gasifying agent come into contact with the gasifier is important [21], and forms the basis for the main current classification of gasifiers.

4.1. Moving bed reactors

Moving bed reactors get their name from the movement in the flow of biomass as it passes through the reactor, though some authors refer to this type of reactor as "fixed bed" because the movement is very slow in the main forward direction. There are two types of moving bed reactor:

- Updraft or countercurrent;
- Downdraft or co-current.

In an updraft reactor the fuel is fed in from the top, and the gas generated also emerges from the reactor via the top. The gasifying agent (air, oxygen, steam or a mixture of them) is heated slightly and enters the gasifier through a grill at the bottom. This agent then rises through the bed of descending biomass or ash in the gasifier chamber.

And as soon as it enters from the bottom of the gasifier, the gasifying agent comes into contact with the hot ash and non converted char dropping from above.

The area above the gasification area is where the pyrolysis of the biomass takes place. The residual heat in the updraft of hot air is transferred to the descending biomass, which is heated and pyrolyzed. In the pyrolysis process the biomass is converted into non-condensable gases, condensable gases and char. Both types of gas rise, and the char drops with the other solids.

At the top, the biomass is dried by the heat transferred to it from the gas updraft. This gas is a mixture of products of gasification and pyrolysis.

In a downdraft reactor the biomass is fed in from the top and drops downwards, while air is injected from one side and mingles with the products of the pyrolysis. From then on both gases and the solids (char and ash) move down in parallel streams through the reactor. Part of the gas generated during pyrolysis may be burned in the gasification area. Thus the heat energy needed for drying, pyrolysis and gasification is provided by the combustion of pyrolytic gas. This is known as "pyrolytic flame" [4].

The reagent areas in a downdraft reactor are different from those in an updraft reactor. Here, the gasifying agent is fed in from the bottom of the gasifier. The products of pyrolysis and combustion drop downwards. The hot gas then moves down, passing through the hot char, where gasification takes place. This arrangement means that the gas produced contains less tar, but it also has less calorific power because of the pyrolytic gases that are burned to provide the energy required for endothermic reactions.

4.2. Fluidized bed reactor

In a fluidized bed reactor the fuel is fed in relatively quickly from the top, onto the whole of the fluidized bed. The gasifying agent is provided in the form of a fluidizing gas fed in from the bottom of the reactor.

In a typical fluidized bed reactor fresh, solid particles of fuel come into contact with the hot bed of solids, which rapidly bring the newly arrived particles up to the bed temperature, so that they undergo rapid drying and pyrolysis, producing char and gases (condensable and non-condensable).

Even if the bed of solids is thoroughly mixed, the fluidizing gas is generally kept in continuous mode, entering through the bottom and exiting through the top.

Fluidized bed reactors cannot achieve full conversion of char due to the continuous mixing of solids. The high degree of mixing of solids helps to maintain an even temperature, but the close mixture of gasified and partially gasified particles means that any solid that leaves the bed contains partially gasified char. The particles of char in trained from the fluidized bed can cause losses in the gasifier.

The other major problem with this type of gasifier is the low level of dissemination of oxygen from bubbles to the emulsion phase. This means that the combustion reaction takes place in the fluidized phase, which decreases the efficiency of gasification.

In a circular fluidized bed (CFB) reactor, the solids move in a circle characterized by thorough mixing and high residence times within the solid circulation loop. The absence of bubbles prevents the gas from bypassing the bed.

Fluidized bed gasifiers typically operate at temperatures of 800–1000 °C to prevent ash from building up. This is admissible for fuels such as biomass, MSW and lignite. These reactors therefore typically have no problems in processing fuels with high ash contents.

Another advantage of this type of gasifier is that its high thermal inertia and vigorous mixing enables it to gasify different types of fuel, e.g. different types of biomass (depending on the season). This is therefore one of the preferred technologies for large-scale biomass gasification plants [4].

4.3. Entrained bed reactors

Entrained bed reactors are preferred in integrated gasification combined cycle (IGCC) plants. They operate at around 1400 °C and with the pressure of between 20 and 70 bar, entraining powdered fuel through the gasifying medium.

Powdered fuel ($<75\ \mu m$) is injected into the reactor chamber along with the gasifying agent. The fuel may be mixed into a paste with water to make it easier to feed into the reactor, especially if it is pressurized. The speed of the gas through the reactor is high enough to entrain all the particles of fuel. Gasifiers fed with this paste of fuel and water need bigger reactor volumes to evaporate the water used in a mixture. They also consume approximately 20% more oxygen than dry in feed systems due to their high draft demands [4].

When oxygen enters this type of reactor it reacts rapidly with the volatile materials and the char, producing exothermic reactions. These reactions raise the temperature above the melting point of the ash, thus completely destroying the tars or oils. These high temperatures should result in a higher level of conversion of carbon [4].

Entrained bed reactors can be seen as piston flow reactors. The gas is rapidly heated to the reactor temperature on entry, but the solids are heated more slowly throughout the reactor due to the thermal capacity of the reactor and the natural piston flow. Some entrained bed reactors are known as continuous mixing reactors, due to the speed with which they mix solids.

4.4. Twin fluidized bed reactors

These reactors are used to produce gas with a higher calorific power than can be achieved with a single gasifier. They comprise two reactors:

– the first acts as a pyrolyzing reactor, heated with sand or a hot inert material from the second reactor;
– the second obtains its heat by burning char from the first reactor.

Gasifiers can also be categorized as follows:

- by their gasifying agents: air, steam, oxygen, CO_2 or a mixture of them;
- by their operating pressure: atmospheric or pressurized;
- by the source of the heat that they require: direct (from the combustion of the biomass itself) or indirect (from an external heat source).

The following general technical points can be made concerning the types of gasifier currently available:

- Fixed and fluidized bed gasifiers cannot achieve high biomass conversion rates, they produce syngas with a low calorific power and their tar content is higher [22].
- Downdraft or co-current gasifiers produce less tars than updraft or countercurrent gasifiers. Fluidized bed gasifiers

produce intermediate quantities between the two. Downdraft gasifiers are more sensitive to fuel types, and have little flexibility in this regard [22].

- Downdraft gasifiers were studied at experimental level by Perez et al. [11], who concluded that the quality of the syngas that they produced could be improved by increasing their diameters.
- Updraft gasifiers are suitable for applications where heat must be generated but the existence of tars is not important [23].
- Fluidized bed gasifiers have the advantage that they enable consistent temperatures to be maintained just below problematic levels that could lead to sintering or a build-up of ash. They produce less char than fixed bed reactors, but could find it difficult to entrain certain particles, which reduces the biomass conversion efficiency [24].

There are around 50 commercial gasifier manufacturers in Europe [21], of which

- 75% produce downdraft or co-current reactors.
- 20% produce fluidized bed reactors.
- 2.5% produce updraft or countercurrent reactors.
- 2.5% produce other types of reactor.

There are also other gasification technologies currently under development, such as:

- *Plasma gasification*, used principally with mainly organic MSW (municipal solid waste), and other wastes such as paper, plastics, glass, metals, textiles, wood, rubber, etc. [25]. "Plasma" is any gas in which at least part of the atoms or molecules are partly or fully ionized. Plasma is formed when an electric arc is generated by running an electric current through a gas. This results in high temperatures in the plasma current which make any molecule within that current break its bonds, thus generating a syngas. At the same time the melting of inorganic components (glass, metal, silicates and heavy metals) gives rise to a slag that vitrifies on cooling. Plasma gasification processes may reach temperatures from 2000 to 30,000 °C. There are systems currently under study that have a fluidized bed gasifier and a plasma process arranged in series [3].
- *Supercritical water gasification*: These systems make use of the conditions of the critical point of water at 647.3 K and a pressure of 22.1 MPa as a favorable environment for wet biomass gasification reactions [26]. Gasification systems with supercritical water are currently the subject of research, with satisfactory results [26]. This system can be used not just for treating wet biomass but also for treating liquid effluent from gasification plants, according to experiments conducted by DiBlasi et al. [27], with products generated during gasification in an updraft reactor processing wood. Hydrothermal gasification with supercritical water is an interesting process, since it enables waste with high moisture contents to be processes without prior drying [28].

As can be seen in Table 3, there are several factors to be taken into consideration when selecting the type of gasifier. Fixed bed gasifiers are used mainly in low-output power plants, and the greater the movement in the bed the greater the plant outputs required for economies of scale.

5. Operating parameters

Once the type of gasification has been chosen according to the biomass to be processed, the next stage involves commissioning and operating the installation, with the aim being to do so as continuously as possible, with high performances and without incidents leading to unwanted stoppages.

The gasification process is more complex than combustion, and there are series of operating parameters that are crucial for the system's proper operation. The very diversity of existing gasification technologies determines some of these parameters, given the intrinsic way in which each one works. This means that there are pressurized and atmospheric gasifiers, with and without particle movement, with recirculation through second reactors installed in series, etc. The optimum values of other parameters should be controlled to obtain a constant quality with high process performances.

5.1. Residence time

The residence time in each type of reactor, which is the average period for which the biomass particles remain inside the gasifier, should be long enough to ensure that the reactions in the gasification process take place satisfactorily, generating the expected syngas. This is linked to the degree of fluidization of the beds, with the time being shorter as there is more stirring in the bed.

With a view to setting the right residence time conditions, the appropriate forced draft systems (fans or blowers) need to be provided. These devices must be catered for at the design stage.

The reactors with the longest residence times are fixed bed gasifiers [24]. Entrained bed gasifiers have short residence times, approximately 1–2 s, during which the small biomass particles are dried, pyrolyzed and then gasified. An optimum time of 1.6 s is proposed for this type of gasifier [22].

5.2. Gasifying agents

Air is the most commonly used gasifying agent, as it is obviously economical. Using air produces a syngas of less calorific power, due mainly to its high N_2 content [24]. Steam as a gasifying agent produces a syngas with a moderate calorific power, and its costs are somewhere between air and oxygen. Oxygen is the gasifying agent required for more advanced applications, and also the most expensive one [1]. CO_2 may also be used as a gasifying agent, as can a mixture of all the above [24].

Hosseini et al. [20] used thermodynamic analysis to study the effect of gasification with air or with steam, with sawdust as the biomass. The exergy and energy efficiencies are observed to be higher with air as the gasifying medium than with steam.

The effect of mixing steam with air was studied by Hernández et al. [29] in an entrained bed gasifier. The results obtained show an optimal range in the steam content of the gasifying agent (found for air–steam mixtures containing 40–70% mol steam) for which a trade-off between gas quality, gas production, and cold gas efficiency is reached.

5.3. Gasifying agent–biomass ratio

The gasifying agent ratio is the ratio of the gasifying agent to the biomass feedstock used in the reactor.

In a fluidized bed reactor with steam (with the latter being used as gasifying agent and fluidizer), it was observed that by keeping the temperature constant at 750 °C and increasing the steam/biomass ratio, the production of H_2, CO_2 and CH_4 increases,

while the amount of CO, decreased, always depending on the types of biomass used [30].

For interconnected fluidized bed gasifiers, where gasification and combustion are conducted separately, there is a proven steam/biomass ratio at which the peak values of H_2 production are recorded in the syngas generated. An increase in the steam/biomass ratio from 0.8 to 1.4, reduces the tar content in the gas generated [31]. The same effect was found in a fluidized bed reactor with an indirect or external heat source, where tars decreased when the steam/biomass ratio was increased from 0.83 to 1.2. The effect became more pronounced as the temperature increased [32]. Moreover, the syngas obtained had a higher H_2 and CO content but a lower content of CH_4 and CO_2.

For entrained bed gasifiers, with oxygen as the gasifying agent, an oxygen–biomass ratio of 0.4 is recommended [22]. According to an experiment by Hernández et al. [29] with entrained beds, an increase in the S/B ratios promotes the char and CH_4 steam reforming and the WGS (water–gas shift) reactions. The production of H_2 is more sensitive to changes in S/B when air is present in the gasifying atmosphere.

Ran et al. [33] demonstrated in a regenerative gasifier with pine biomass that the best steam/coal ratio was 0.3, with 5.6 MJ/N m^3 of syngas being produced.

In an External Circulating Countercurrent Moving Bed (ECCMB) gasification system, Zou et al. [10] demonstrated at experimental level that the optimum steam/biomass ratio was 1.2. They obtained 35% of H_2 and 12% of CO.

5.4. Air–fuel ratio and equivalent ratio (ER)

The air–fuel ratio is the ratio between the air and fuel used, which is considerably lower than in combustion processes, which operate with excess stoichiometric air, whereas gasification involves default air values:

$$r_{air-fuel} = \frac{mol\ of\ air}{mol\ of\ fuel}$$

The equivalent ratio (ER) is the ratio between the air–fuel ratio for the current process and the air–fuel ratio for complete combustion.

The equivalent ratio would have a value of 1 for combustion, and would be expressed as follows:

$$\text{ER} = \frac{r_{air-fuel\ (actual)}}{r_{air-fuel\ (complete\ combustion)}}$$

The air–fuel ratio is considered to have the greatest influence on the final calorific power of the syngas generated [30]. Suitable values of the ER for gasification fall within the 0.2–0.4 range, thereby enabling the generation of tars and char to be controlled [24].

By increasing the ER and keeping the biomass flow constant, the gasifier's temperature increases, as there is more oxygen per volume of biomass for conducting the partial combustion reactions, which are the ones that generate the necessary energy [18].

Hosseini et al. [20] used thermodynamic analysis to demonstrate the effect on energy efficiency of increasing the ER with different biomass moisture levels. They found that efficiency decreased with the same trend regardless of whether air or steam was used as the gasifying agent.

5.5. Reaction temperature

The reaction temperature is one of the more important parameters. According to Enami et al. [34] it is the most significant parameter in gasification, so it needs to be controlled accurately, as depending on the type of fuel it can cause problems of ash build-up or sintering. Reducing the temperature to control this unwanted phenomenon leads to lower char conversion (reducing process efficiency) and a higher concentration of tars in the syngas generated (limiting its use in certain electricity conversion equipment) [35].

Raising the temperature increases the concentration of CO and H_2 in the syngas and reduces that of CO_2, CH_4 and H_2O [34,36].

Once again, within the existing range of gasifiers, the degree of bed fluidization is directly related to temperature differences in the reactor, with these being lower and therefore more uniform as the bed is more fluidized.

Numerous tests have been conducted on gasifier operating temperatures and the ramifications of varying them. There follows a description of some of them, according to the type of reactor.

A downdraft reactor fed with sawdust and with steam as its gasifying agent, intended mainly to produce H_2 for charging a solid oxide fuel cell (SOFC), was set up to operate between 1023 and 1423 K, at atmospheric pressure, according to Abuadala [37].

In a bubbling fluidized bed reactor with steam acting as both gasifying agent and fluidizer, an increase in the reaction temperature while keeping the steam/biomass ratio constant increases the H_2 and CO contents of the syngas generated and reduces the CO_2 and CH_4 contents, with this circumstance varying according to the types of biomass used. This phenomenon was experimentally observed and then modeled in the 650–800 °C temperature range with a constant tendency [30].

In a fluidized bed reactor with an indirect or external heat source and steam as its gasifying agent, it was found that an increase in temperature from 750 to 840 °C considerably reduced the amount of tars in the syngas produced, increased the content of H_2 and CO and decreased the content of CH_4 and CO_2 [32].

In another case involving a fluidized bed, denser phases and lighter ones were detected, generating a uniform temperature profile in each phase, with higher temperatures in the denser phases. Bed temperature has a direct influence on the calorific power of the syngas generated: the latter drops linearly as the former increases. This explains why maintaining a higher temperature in the gasifier requires more combustion, leaving less material to be gasified. An increase in bed temperature increases H_2, O_2 N_2 and CO_2 contents and reduces CH_4 and CO contents [18].

The temperatures in an entrained bed are higher, and may be around 1300–1500 °C. An increase in reactor temperature leads to an increase in H_2 and CO contents and a decrease in CO_2 and CH_4 contents in the syngas generated [22]. This is an important finding, as H_2 and CO are the components with the greatest bearing on syngas quality. An increase in temperature improves the quality of the syngas.

Hernández et al. [29] found in an experiment that in an entrained bed gasifier an increase in the operating temperature had different effects depending on the gasifying agent used. Air gasification mainly increases the CO and H_2 content in the product gas via the endothermic Boudouard and steam reforming reactions, whereas gasifying with air–steam (~56.4% mol steam) leads to a boost in the H_2 production due to the enhancement of the char-steam reforming and WGS (water–gas shift) reactions, as well as an increase in the CH_4 content.

Ran et al. [33] developed a regenerative gasifier that used the heat of the syngas to heat up the gasifying agent through a ceramic heat exchanger with a honeycomb structure. They managed to increase the gasification temperature with a lower ER and produced a syngas of 5.4 MJ/N m^3.

In gasification with supercritical water, the study through a mathematical model of the influence of the temperature has shown that the value of 600 °C leads to the best gasification efficiency (more than 85%) with a gas lower heating value of 6.31 MJ/kg when no air is added to the system and 5.41 MJ/kg in the autothermal mode of operation [38].

The main problems arising from the gasification process involve temperature. If the temperature increases considerably, there may be problems of sintering, build-up, erosion and corrosion. Alkaline metals such as potassium may give rise to alkaline silicates and sulfates, which have melting points even below 700 °C, and they may become attached to the reactor walls forming deposits that reduce process efficiency. Furthermore, the presence of these compounds in the syngas may cause similar problems in the electricity conversion equipment receiving the gas generated [24].

5.6. Pressure

Depending on the pressure used, there are two types of gasification process: at atmospheric pressure or pressurized (at higher pressures). The latter are more efficient, although they also imply high investment costs.

An increase in the operating pressure of gasifiers reduces the amount of char and tar in the syngas generated. Furthermore, the syngas is obtained already pressurized for subsequent use in end conversion equipment, such as engines or turbines [24]. However, experiments conducted with a fluidized bed reactor with external heat source have shown that the proportion of tars increases when the pressure rises from 0.10 to 0.25 MPa, mainly due to the increase in naphthalene, so that the CO content in the syngas decreases and the CH_4 and CO_2 increase [32].

According to Klimantos et al., combined-cycle gasification systems based on pressurized cycles coupled to hot gas cleaning systems are one of the most promising options, recording efficiencies of more than 40% [39]. The greater commercial availability of gas turbines would favor this type of solution.

Pressurized systems are used in large plants, but they are uneconomical at small scale [1].

A gasification system coupled to an SOFC and gas turbine was modeled to show that an increase in atmospheric pressure up to 4 bar did not have a major impact on the gasification process, although it did affect turbine efficiency and, therefore, the unit's overall efficiency, which increased from 23% to 35% [40].

6. Cleaning system

6.1. Amount of tars in the syngas

The formation of tars is one of the biggest problems to be faced in gasification. The treatments that can be undertaken to control their formation are divided into those carried out inside the gasifier (primary processes), and those carried out in the hot cleaning of the gases generated (secondary processes) [21]. In economic terms, the ones of greater interest are the primary processes inside the gasifier, although they have not yet been suitably developed.

The formation of tars depends on several factors, namely:

- Temperature
- Gasifying agent
- Equivalent ratio
- Residence time
- Catalyst additives, such as dolomite and others, which significantly convert the tars, reducing their content in the gases generated.

The configuration of the gasifier and the right combination with the use of catalysts are key in reducing tars. Brandt and Larsen [41] observed a reduction in tars in a two-stage gasifier with pyrolysis in stage one and gasification in stage two on a charcoal bed. A similar reduction in tars was observed by Nunes et al. [42] in an experiment with two downdraft gasifiers in series.

The type of gasifier selected also influences the formation of tars. Qin et al. [9] conducted an experiment with an atmospheric entrained bed gasifier at high temperatures (up to 1350 °C) that revealed no tars (though there was some soot), with cereal straw and wood as fuel.

A pilot scale gasification unit with a novel co-current, updraft arrangement in the first stage and counter-current downdraft in the second stage was developed and operated by Šulc et al. [17] for the study of two stage gasification in comparison with one stage gasification of biomass (wood pellets) on fuel gas composition and attainable gas purity. The experimental gasification data clearly demonstrated that two stage gasification with gasification temperature in the first stage about 670 °C and ER=0.32 and in the second stage 950 °C (overall ER=0.71) could produce relatively clean gas, with low concentrations of tar compounds. The disadvantage of such a technological arrangement was the relatively low calorific power of the fuel gas (LHV about 3.15 MJ/N m^3).

Catalysts can be added directly to the bed itself or together with the biomass feed. Depending on their nature, they can be divided into synthetic (produced by chemical methods at a relatively high cost, such as activated aluminum) and mineral (produced naturally and therefore more economical, such as calcite and clay minerals) [43].

In a fluidized bed gasifier the selection of the inert material for the bed in suspension influences the composition of the syngas and the tar concentration [44].

Siedlecki found that using magnetite as a catalyst or as an inert bed rather than quartz sand and olive waste resulted in the biggest reduction in tars in a circulating fluidized bed reactor with steam and oxygen as gasifying agents [45]. Nemanova et al. showed that the use of iron base metal granules also resulted in a major reduction in tars in the syngas produced in an atmospheric fluidized bed reactor with birch wood as biomass fuel [46,47].

In an External Circulating Countercurrent Moving Bed (ECCMB) gasification system with pine sawdust, Zou et al. [10] showed in an experiment that an increase in the catalytic bed height in the gasifier improved the gas yield, chemical efficiency and catalytic destruction of tar.

Another factor that has an impact on tar formation is the size of the biomass particles. Gaston et al. report that the amount of tar generated in a fluidized bed gasifier increased with the size of the oak spheres used [48]. Innovative optical methods such as fluorescence spectroscopy can be used for detection of tars in the syngas generated [49].

6.2. Gas cleaning

Besides the syngas that is the object of the gasification process, other unwanted substances are generated. Monitoring of the particles in these substances (dust, fly ash, tars, ammonia, sulfur compounds and others) should begin in the gasifier with the selection of appropriate operating parameters, their proper design and the use of the right additives and catalysts [50]. This will reduce the need for a subsequent cleaning of the syngas generated [24].

There are two different ways of cleaning the gases generated: cold and hot. Hot cleaning systems increase gasification efficiency by around 3–4%, as the syngas carries a greater amount of energy than when it is cooled. [39].

The main components of a gas cleaning system for the removal of dust, particles and tars are as follows [24]:

- Cyclones
- Ceramic, textile, bag filters, etc.
- Rotating particle separators
- Wet electrostatic precipitators
- Water scrubbers

Entrained bed gasifiers use an arrangement on the upper part to cool the syngas and remove the tars, whereupon it passes through a cyclone, filter and condenser mounted in series [22].

These systems remove or capture the tars in the syngas, thereby discarding all the energy they contain. Catalytic cracking of the tar or thermal cracking is used to decompose or reduce the tars, although these methods have certain disadvantages [51].

Tars and ammonia can be removed using hot cleaning technology through steam or dry catalytic reforming or by catalytic means involving tar cracking/hydrocracking reactions, as well as the catalytic decomposition of ammonia to form N_2 and H_2. These processes perform poorly and are of limited use in large plants, and more research is required into their possible implementation [52]. Tests have been conducted at laboratory scale on fluidized bed gasifiers with commercial sorbents, such as ZnO, for the removal of sulfur compounds [50].

7. Conclusions

Gasification is a complex technology that is inflexible, less competitive than others, as yet not mature and, therefore, subject to certain risks. It is not a sound alternative for generating electricity.

First, it is complicated to choose the right gasifier for a given plant size, and one that is suitable for the biomass to be used, as there is a very wide range of designs and set-ups, many of which are still at the research stage, and biomass does not have the same steady behavior as fossil fuels.

In addition, plant operation is more complex than with combustion, and it is sensitive to numerous parameters, which means that it may incur unwanted operating instabilities.

Furthermore, a plant's operating regime depends on variables that cannot always be controlled, mainly the uniformity and availability of the biomass.

This study leads to the following conclusions:

1. The parameters with the greatest impact on the gasification process are the gasification reaction temperature and the equivalent ratio. The two are interrelated. The control of these parameters ensures that (i) a syngas with an acceptable content of tars and particles is produced and (ii) there are no unwanted ash sintering effects caused by high temperatures in the reactor.
2. Biomass moisture content is an operating parameter that reduces gasification efficiency, as part of the energy is used for drying the biomass. Furthermore, moisture contents above 15% lead to variations in the concentration of the components of the syngas generated, and therefore in its calorific power, thereby rendering the process unstable. Prior biomass preparation processes, such as pyrolysis or torrefaction, may help to provide the fuel with energy regularity, and so stabilize gasification. An estimation will have to be made of the energy costs of the prior processes, with an assessment of their viability.
3. The presence of tars in the syngas generated is one of the main technology barriers to the development of gasification. Current proposals involve acting upon the gasifier, through (i) its design, (ii) the optimal setting of the operating parameters that have a direct bearing on the amount of tars generated, and (iii) the use of catalysts and additives or, as a second option, the application to the flow of syngas generated of techniques for cleaning or converting the tars.
4. Once the syngas has been obtained, it is difficult and costly to ensure that it meets the ideal conditions required. In addition to tars, other particles and ashes need to be removed. Many cleaning techniques are also at the research stage. What is more, the makers of some of the energy conversion equipment will not commit to guaranteeing its operation under certain conditions.
5. The design of a gasification plant requires consideration of some factors that may experience significant variations during operation (mainly composition of biomass). These fluctuations generate instability in the operation of the plant.

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